

# Icing of Flow Conditioners in a Closed-Loop Wind Tunnel

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# ICING OF FLOW CONDITIONERS IN A CLOSED-LOOP WIND TUNNEL

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## SUMMARY

This report describes the results of an experiment which determined whether flow conditioning screens and honeycombs would ice up in a closed-loop icing wind tunnel when placed downstream of the heat exchanger and upstream of the spray bars. The experiment was performed in the Icing Research Tunnel (IRT) at NASA Lewis Research Center. The investigation involved two separate tests: one to find the icing characteristics of flow conditioners in the IRT, and the second to find the icing characteristics of flow conditioners in the proposed rehabilitation of the Altitude Wind Tunnel (AWT). Both experiments showed that the heat exchanger removed nearly all of the icing cloud so that icing of the flow conditioners would cause no serious tunnel performance degradation during the course of a day's run. Only extremely cold conditions caused frost formation on the flow conditioners. The significance of this frost formation was minimized because frost buildup on the heat exchanger caused a much more severe pressure drop than did icing of the flow conditioners.

## INTRODUCTION

In closed-loop icing wind tunnels, as in any wind tunnel, it is desirable to improve the quality of air flow by placing screens and honeycombs in the tunnel. In ice tunnels the flow conditioners would be placed upstream of the spray bars and downstream of the heat exchanger. These flow conditioners must remain relatively free of frost and ice buildup during the course of a run. Failure to do so would result in premature tunnel shutdown or destruction of the screens due to the differential pressure.

Since the flow conditioners would be located between the heat exchanger and the spray bars in both the Icing Research Tunnel (IRT) and the proposed Altitude Wind Tunnel (AWT) at NASA Lewis, it is essential that the heat exchanger remove the remaining portion of the spray cloud and condensed moisture. Note that 40 to 90 percent of the total spray cloud reaches the heat exchanger (ref. 1).

The purpose of this experiment was to determine whether flow conditioners can be used in both the IRT and the proposed AWT with little or no ice or frost buildup during a day's run. Two experiments were required, since it is essential that the screens be tested behind the appropriate heat exchanger. Both experiments were performed in the IRT. A description of the IRT is given in reference 1. Reference 2 describes the proposed AWT.

The first test involved placing a piece of screen just upstream of the spray bars. The screen was visually inspected for ice and frost formation over a period of 4 months. No pressure drop measurements were made. The

second test was run in the backleg of the IRT behind a segment of the heat exchanger recommended for the AWT. Pressure drop measurements were made across the heat exchanger and the screen and honeycomb as a function of spray time.

Data from this experiment are applicable to any closed-loop icing wind tunnel that has similar tunnel components in a similar orientation to the IRT. Figure 1 shows the following IRT components: test section, two sets of turning vanes, foreign object deflection screen, inlet guide vanes, one- or two-stage fan, another set of turning vanes, a heat exchanger, and a final set of turning vanes. The flow conditioners would be placed between the final set of turning vanes and the spray bars. Reference 1 reports the percentage of the icing spray each component removes in the IRT and shows the amount each component is expected to take out in the AWT.

### SYMBOLS

DVM	droplet volume median, $\mu\text{m}$
k	pressure loss coefficient
LWC	liquid water content, $\text{g}/\text{m}^3$
P	total pressure drop, Pa
Q	dynamic pressure, Pa

### EXPERIMENT 1

The first experiment was strictly a qualitative test. A fine mesh screen was placed just upstream of the spray bars where flow conditioners would be placed in the IRT (fig. 1). The screen was visually inspected for ice or frost formation. Since this screen would catch any droplets remaining in the air-stream, this experiment was a simple way to determine whether the heat exchanger removes all the remaining spray cloud and condensed moisture.

The test covered a broad range of tunnel conditions. The IRT total temperatures varied from  $-4$  to  $-29$   $^{\circ}\text{C}$  ( $25$  to  $-20$   $^{\circ}\text{F}$ ). Liquid water content (LWC) and drop volume median (DVM) diameter ranged from  $0.7$  to  $1.6$   $\text{g}/\text{m}^3$  and  $10$  to  $25$   $\mu\text{m}$ , respectively. The screen remained in the tunnel for 4 months and was visually inspected during each night that icing tests were run in the IRT.

The screen tested was a square,  $1.2$ - by  $1.2$ -m ( $4$ - by  $4$ -ft), 316 stainless steel wire cloth. There were 12 mesh per linear inch, and the wire diameter was  $0.58$  mm ( $0.023$  in.). This resulted in an open area ratio of 52.4 percent. The screen was attached to the spray bar support structure 6 ft above the ground. Figure 1 shows this location in the IRT.

For the entire 4 months that the screen occupied the tunnel, no ice formed on the screen because of the icing spray. The heat exchanger removed all of the remaining cloud so that no icing occurred on the screen (i.e., the icing spray did not recirculate around the tunnel). One tunnel condition, however, did cause frost formation on the screen. This condition occurred when the tunnel total temperature was  $-29$   $^{\circ}\text{C}$ . At this condition the air downstream of the heat exchanger was supersaturated. The supersaturated condition was evident by seeing wisps of cloud flow through the test section after turning off

the spray bars. Figure 2 shows the frost formation on the screen after 1 hr of spray time.

This experiment demonstrated that (1) the IRT heat exchanger removed essentially all of the simulated icing cloud, and that (2) frost formed on a fine screen only when the air downstream of the heat exchanger became supersaturated.

## EXPERIMENT 2

The second experiment was performed to investigate the icing characteristics of flow conditioners for the proposed rehabilitation of the AWT. The experiment was necessary to determine whether flow conditioners could remain in the AWT when it was used for icing tests. Total pressure drops were measured across the flow conditioners. A detailed study of the flow conditioners for the AWT can be found in reference 3.

### Test Apparatus

The experiment was performed in the backleg of the IRT (fig. 1). The IRT was selected because it provided the cold environment and the spray conditions necessary to simulate conditions in the AWT.

The major pieces of hardware used in this test included (1) a segment of the heat exchanger recommended for use in the AWT, (2) a segment of screen and honeycomb recommended for use in the AWT, (3) duct work to contain the heat exchanger and the screen and honeycomb, and (4) a centrifugal fan with axial flow inlet and outlet. Figure 3 shows the duct work configuration with the location of items (1), (2), (3), and (4). A description of item (1) together with data on its performance in icing conditions can be found in reference 4. Note that the duct transitioned from a rectangular 0.91- by 0.9-m (36.0- by 35.4-in.) cross section downstream of the heat exchanger to a 0.71-m- (28-in.-) diameter cross section just upstream of the screen. The duct contained viewing ports, which permitted visual inspection of the heat exchanger and the screen. Figure 4 is a photograph of the duct installed in the IRT.

One screen and honeycomb configuration was run. As figure 3 shows, the screen was located upstream of the honeycomb. The screen was a fine mesh with 34 mesh per linear inch with 0.17-mm- (0.0066-in.-) diameter stainless steel wire. This resulted in an open area ratio of 60 percent. The honeycomb, made of aluminum, had 0.953-cm (0.375-in.) cells that were 10.16 cm (4 in.) deep. This was the only configuration run since it represented the worst possible geometry for icing. The fine mesh screen would catch and accrete any remaining portion of the icing cloud that the heat exchanger did not remove.

The fan had a set of damper vanes at the inlet so that the flow could be adjusted from 0 to a maximum flow rate of about 13.6 kg/sec (30.0 lbm/sec).

The flow conditioners in this test setup were in the same relative position with respect to the heat exchanger and spray bars as they would be in the AWT.

## Instrumentation

Total and static pressures and total temperature were measured in four duct locations. These locations were upstream and downstream of both the heat exchanger and the screen and honeycomb (fig. 3). Total pressures were measured by using total pressure rakes, and static pressures were measured by using eight wall static taps at each of the four locations. Total temperatures were measured by Chromel-constantan thermocouple probes located on the total pressure rakes. The thermocouples were referenced to a 65 °C (150 °F) oven.

An electronically scanned pressure (ESP) system was used to measure the pressures. This system used 6.89-kPa (1-psid) differential modules for all the pressure measurements. Atmospheric pressure was used for the reference side of the modules. The accuracy of these modules was  $\pm 3.8$  Pa ( $\pm 0.002$  psi).

## Data Reduction

Average total pressures were calculated in two ways. Average pressures upstream and downstream of the heat exchanger were calculated by an area-weighted average. The total pressure probes were placed in equal areas. Average total pressures upstream and downstream of the screen and honeycomb were calculated by integrating the total pressure profiles, since they were not area-weighted rakes.

The average static pressures were measured by manifolding the eight wall statics at each radial location and forming one pressure line, which went to the ESP module.

Average temperatures at each location were found by taking an arithmetic average of the thermocouples. There were eight thermocouples upstream and downstream of the heat exchanger and five thermocouples upstream and downstream of the screen and honeycomb.

The dynamic pressure was the difference in the average total and static pressure at each of the four areas where pressures were measured.

## Procedure

The icing characteristics of the screen and honeycomb were investigated as a function of the test section total temperature and spray time. The test section velocity, LWC, and DVM size were held fixed at 67.1 m/sec (150 mph) nominal, 1.36 g/m<sup>3</sup>, and 15  $\mu$ m, respectively. The LWC and DVM were set by the air and water pressure at the nozzles. Under these conditions about 90 percent of the spray cloud reaches the heat exchanger (ref. 1). Data were taken at four different tunnel temperatures: -20, -17.8, -11.1, and -3.9 °C (-4, 0, 12, and 25 °F).

After the tunnel reached the desired temperature, the icing cloud was sprayed for a set time, usually between 15 and 20 min. After the spray was shut off, frost formation on the total pressure probes needed to be removed before a data point was taken. The total and static pressure taps were purged during the spray to prevent moisture from entering the pressure lines. After

clearing the total pressure probes the tunnel was taken back up to speed and a data point was taken. Another spray was started after the data reading. Total spray times varied from 20 to 95 min.

## RESULTS AND DISCUSSION

The icing characteristics of the screen and honeycomb are presented here. Icing characteristics of the AWT heat exchanger segment are also discussed.

The total pressure loss coefficient  $k$ , defined as the difference in the average total pressure divided by the local dynamic pressure, is plotted as a function of spray time for the screen and honeycomb in figure 5. Only the two coldest temperatures,  $-20$  and  $-17.8$  °C ( $-4$  and  $0$  °F), caused ice/frost formation, which resulted in an increase in total pressure loss. The loss coefficient increased across the screen and honeycomb from 1.3 to 4.0 after 40 min of spraying the icing cloud. Visual inspection of the screen after the 40 min showed that a light frost formed on about 40 percent of the screen surface area. Figure 6 shows the screen at the  $-17.8$  °C condition. For the warmer temperatures,  $-11.1$  and  $-3.9$  °C ( $12$  and  $25$  °F), the screen remained virtually free of frost. The slight upward trend for the  $-3.9$  °C is due to a very light amount of frost covering approximately 30 percent of the screen surface area. For all four conditions the honeycomb remained clear of ice and frost formation.

The nominal velocity at the screen and honeycomb section when no icing cloud was sprayed, with the fan running at its maximum capacity, was 27.4 m/sec (90 ft/sec). This velocity matched the maximum velocity that would approach the screen and honeycomb in the proposed AWT. Unfortunately this velocity could not be maintained throughout the duration of each run. Blockage due to ice formation on the heat exchanger caused substantial reduction in the airstream velocity (e.g., from 27.4 to 10.1 m/sec (90 to 33.1 ft/sec) after 50 min of spraying at the  $-17.8$  °C ( $0$  °F) condition). Although a reduction in velocity affects the rate of ice accretion on the screen, the screen's fine mesh size and small wire diameter ensure a high collection efficiency. Thus, if there were particles to catch, the screen would catch them. Collection efficiency is defined as the mass of the cloud removed by the screen divided by the total mass of the cloud reaching the screen.

The total pressure loss across the heat exchanger was much more sensitive to ice formation than that across the screen and honeycomb (fig. 7). Ice formed on the first set of fins and tubes at  $-20$ ,  $-17.8$ , and  $-11.1$  °C ( $-4$ ,  $0$ , and  $12$  °F). In general, colder tunnel temperatures resulted in more severe icing on the heat exchanger. The  $-20$  °C case shown in figure 7 came close to completely plugging up the heat exchanger after 20 min of icing. After 40 min the heat exchanger was completely plugged with ice. This is illustrated in figures 8 and 9. Figure 8 is a plot of dynamic pressure  $Q$  as a function of spray time. For the  $-20$  and  $-17.8$  °C cases the dynamic pressure decreased from 95 to  $<20$  Pa ( $0.014$  to  $<0.003$  psi) after 40 min of spraying. Figure 9 is a photograph of the ice buildup on the heat exchanger after 40 min of icing at the  $-20$  °C condition. Notice that the ice is white and that it completely plugs the air passages between the fins. These icing results are consistent with those of reference 4.

An additional case was run at  $-28.9^{\circ}\text{C}$  ( $-20^{\circ}\text{F}$ ) to duplicate the only case which caused frost formation on the screen in experiment 1. This case caused the worst frosting condition on the screen (about 70 percent of the screen area was covered with frost), and the heat exchanger was completely plugged with ice after 10 min of spray.

A tabulation of all the data for the different runs is listed in table I. These data include total pressure loss, dynamic pressure, and mass flow rates as functions of spray time. The pressure drop data across the screen and honeycomb and across the heat exchanger indicate that the frost buildup on the screen and honeycomb is not as important as the ice/frost buildup on the heat exchanger considered for the AWT. This is evident from the plots of  $k$  versus spray time for the heat exchanger and the flow conditioners. A comparison of figures 6 and 7 shows that the pressure drop across the heat exchanger due to ice formation is an order of magnitude greater than pressure drop due to ice on the flow conditioners.

#### CONCLUDING REMARKS

Icing characteristics of flow conditioning screens and honeycombs in an icing tunnel were determined. The conclusions are as follows:

1. Screens and honeycombs can be placed in the IRT and AWT downstream of the heat exchanger and upstream of the spray bars with little chance of becoming plugged with ice or frost buildup.

2. Under the severe conditions of long icing sprays and cold temperatures some frost forms on the screen. The effect of screen frosting on the overall tunnel performance is minimized because the heat exchanger is much more sensitive to the frost and ice formation (i.e., the heat exchanger becomes plugged with ice well before the screen).

3. Since frost can form on the screen, it is recommended that the total pressure drop be monitored across the flow conditioners.

#### REFERENCES

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2. Blaha, B.J.; and Shaw, R.J.: The NASA Altitude Wind Tunnel: Its Role in Advanced Icing Research and Development. AIAA Paper 85-0090, Jan. 1985.
3. Burley, R.; and Harrington, D.: Evaluation of Honeycomb/Screen Configurations and the Short Contraction Section for the NASA Lewis Research Center's Altitude Wind Tunnel (AWT). NASA TP-2692, 1987.
4. Van Fossen, G.J.: Heat Transfer and Pressure Drop Performance of a Finned-Tube Heat Exchanger Proposed for Use in the NASA Lewis Altitude Wind Tunnel. NASA TM-87151, 1985.

TABLE I. - SUMMARY OF ICING TESTS FOR HEAT EXCHANGER, SCREEN, AND HONEYCOMB

Spray temperature		Spray time, min	Velocity at screen		Heat exchanger			Screen and honeycomb		
°C	°F		m/sec	ft/sec	Pressure loss coefficient, k	Dynamic pressure, Q		Pressure loss coefficient, k	Dynamic pressure, Q	
						Pa	psi		Pa	psi
-28.9	-20	0	----	----	13.75	103.4	0.015	----	----	----
		20	----	----	159.38	13.8	.002	----	----	----
		30	----	----	764.5	0	0	----	----	----
-20	-4	0	25.8	84.7	17.1	89.6	.013	1.29	434.4	0.063
		20	19.9	65.3	38.9	55.2	.008	2.04	248.2	.036
		40	8.8	28.9	333.6	0	0	3.76	34.5	.005
-17.8	0	0	27.4	89.9	15.8	89.6	.013	1.10	462.0	.067
		15	26.0	85.3	27.3	68.9	.010	1.23	351.6	.051
		20	22.0	72.2	26.5	68.9	.010	2.02	344.7	.050
		30	15.2	49.9	75.7	27.6	.004	2.35	179.3	.026
		40	11.4	37.4	124.1	13.8	.002	4.07	96.5	.014
		50	10.1	33.1	167.8	13.8	.002	11.83	34.5	.005
-11.1	12	0	27.6	90.5	10.5	117.2	.017	1.15	524.0	.076
		30	23.1	75.8	23.6	75.8	.011	1.29	344.7	.050
		50	22.0	72.2	26.4	68.9	.010	1.68	289.6	.042
		74	19.4	63.6	38.6	48.3	.007	1.74	268.9	.039
		94	16.3	53.5	53.6	34.5	.005	2.28	206.8	.030
- 3.9	25	0	27.9	91.5	12.0	96.5	.014	1.18	496.4	.072
		15	27.0	88.6	13.7	89.6	.013	1.35	399.9	.058
		45	26.2	85.9	15.5	89.6	.013	1.34	420.6	.061



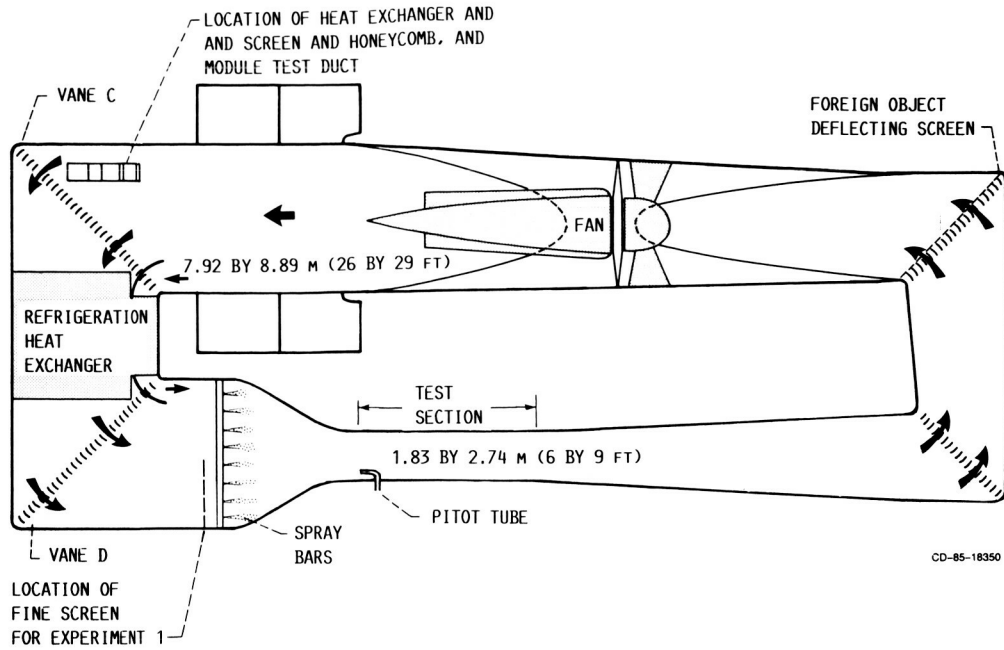


FIGURE 1. - SCHEMATIC OF ICING RESEARCH TUNNEL.



FIGURE 2. - FROST FORMATION ON SCREEN FROM EXPERIMENT 1 AFTER 1 HR OF SPRAY TIME AT A TUNNEL TEMPERATURE OF  $-29^{\circ}\text{C}$  ( $-20^{\circ}\text{F}$ ).

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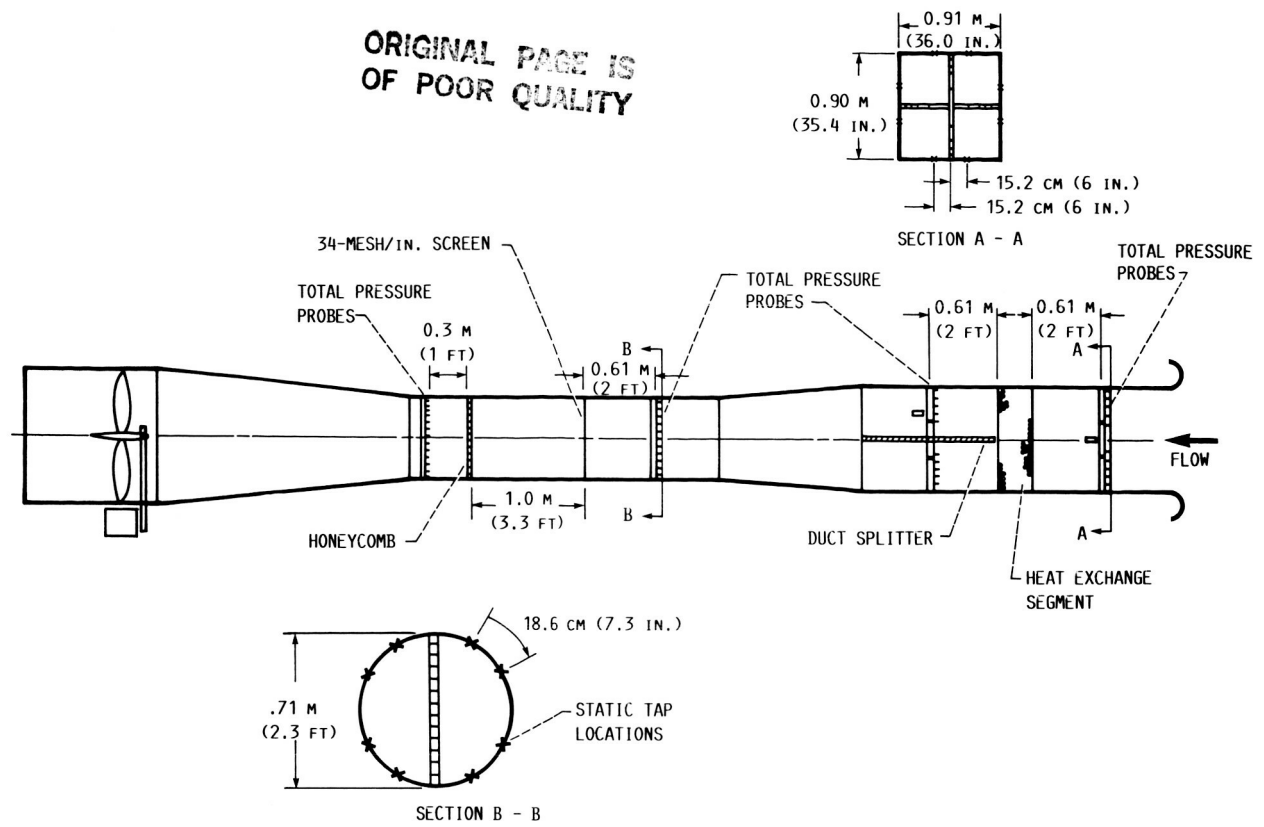


FIGURE 3. - SCHEMATIC OF HEAT EXCHANGER AND SCREEN AND HONEYCOMB DUCT.

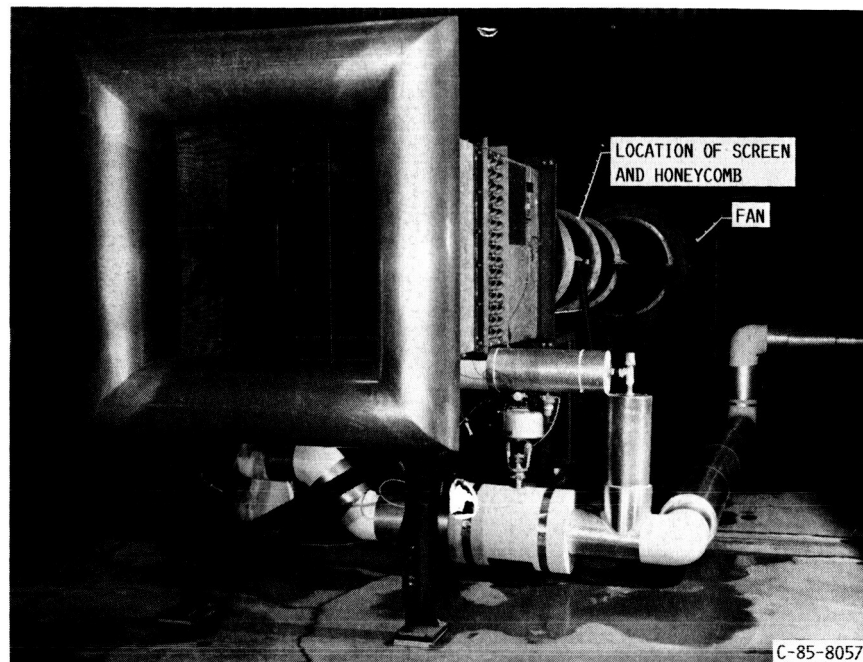


FIGURE 4. - HEAT EXCHANGER AND SCREEN AND HONEYCOMB DUCT.

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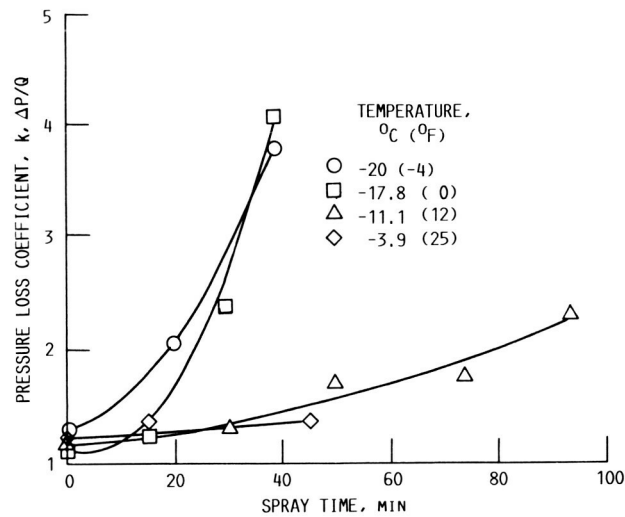


FIGURE 5. - TOTAL PRESSURE LOSS ACROSS SCREEN AND HONEY-COMB AS FUNCTION OF SPRAY TIME.

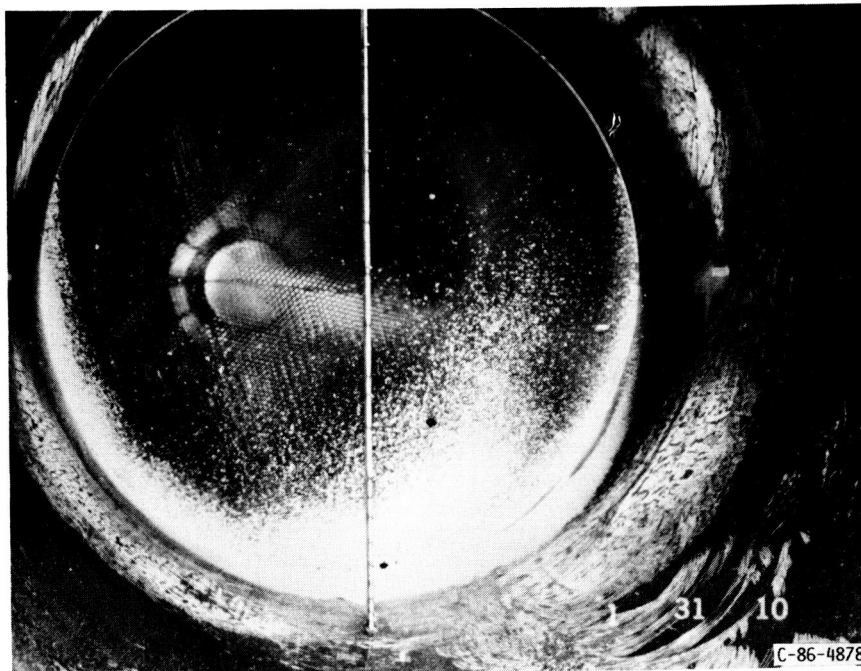


FIGURE 6. - FROST FORMATION ON SCREEN AFTER 40 MIN OF SPRAY TIME AT A TUNNEL TEMPERATURE OF -17.8  $^{\circ}\text{C}$  ( $0^{\circ}\text{F}$ ).

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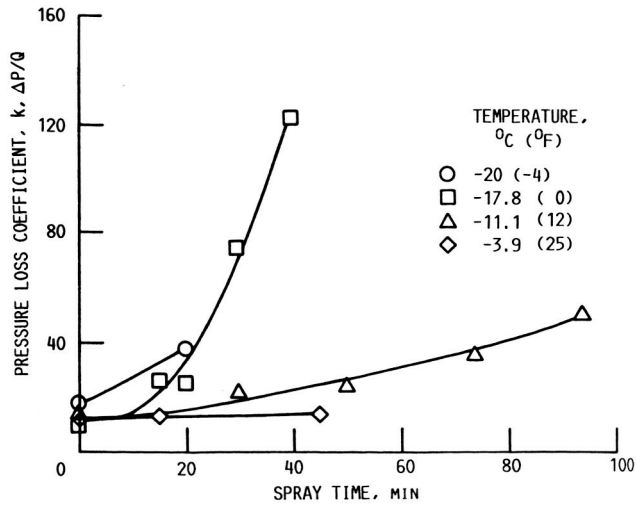


FIGURE 7. - TOTAL PRESSURE LOSS ACROSS HEAT EXCHANGER AS FUNCTION OF SPRAY TIME.

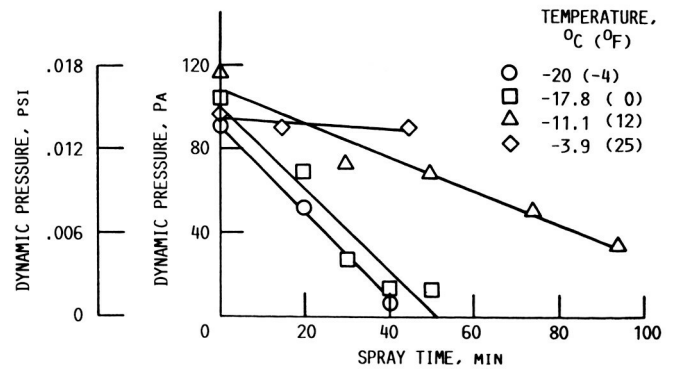


FIGURE 8. - DYNAMIC PRESSURE REDUCTION AT HEAT EXCHANGER AS FUNCTION OF SPRAY TIME.

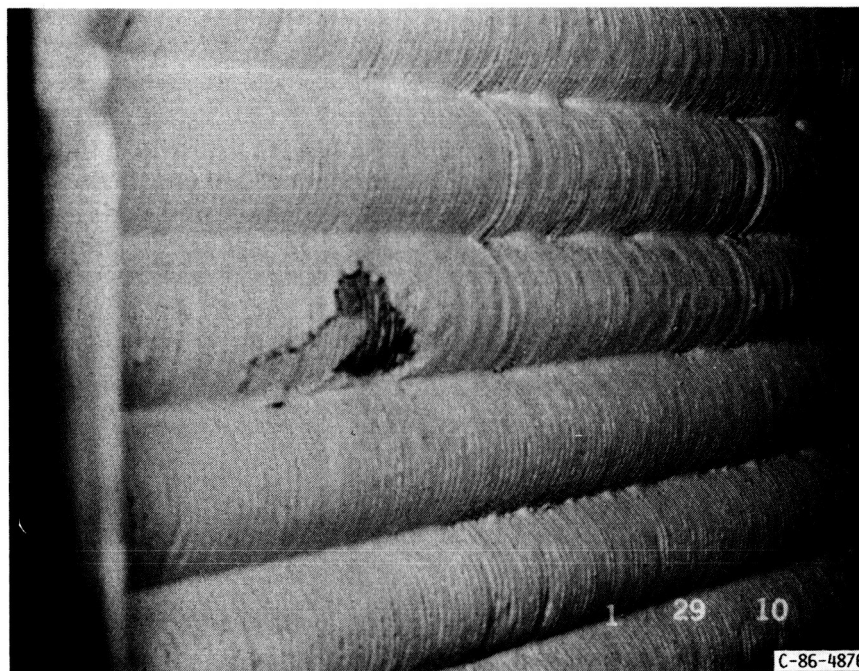


FIGURE 9. - ICE BUILDUP ON HEAT EXCHANGER AFTER 40 MIN OF SPRAY TIME AT A TUNNEL TEMPERATURE OF  $-20^{\circ}\text{C}$  ( $-4^{\circ}\text{F}$ ).

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